

# Strange at LHC

## SnowMass LoI “Strange decays at the LHC”

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Snowmass 2020

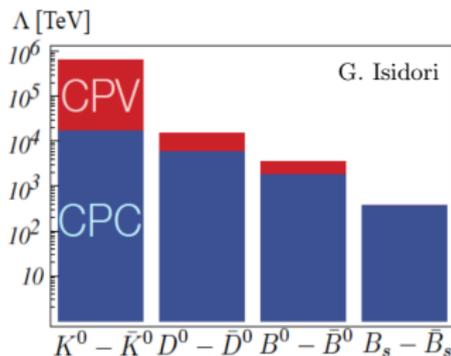
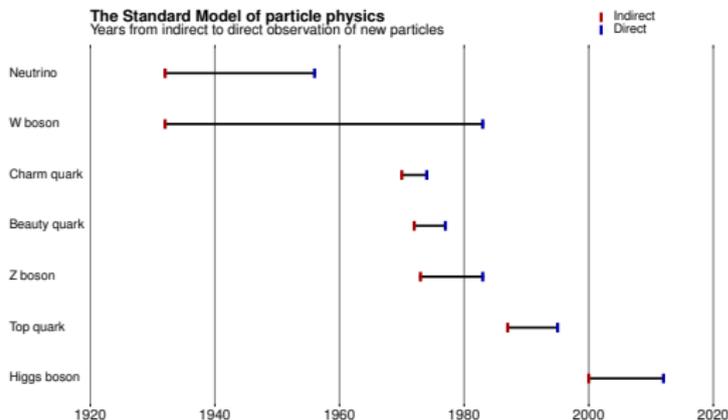


# Why strange?

Strange physics as the bird of flavour physics

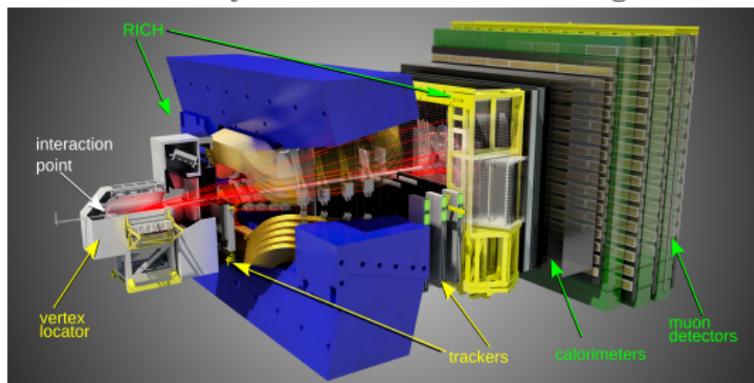
Fostered numerous discoveries in particle physics: new quarks, families and CPV

- Complementary to the more studied  $b$  and  $c$
- Why not? Several observables have very large theory uncertainties
- Still the reign with higher (indirect) energy rich
- Rare decays and CPV sensitive to possible new dynamics

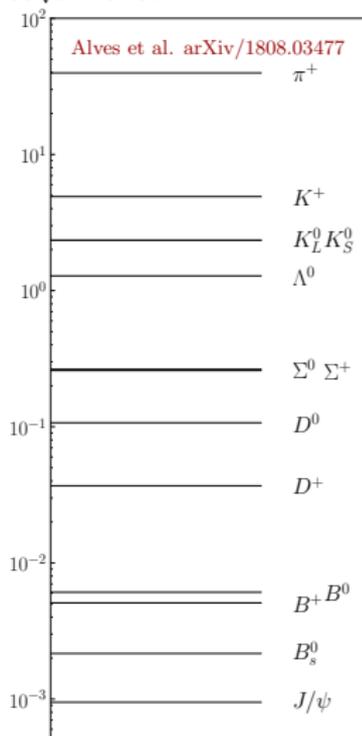


# Strange hadrons at the LHC

- Huge strange hadrons cross-section at LHC
- Production mostly in the forward region, perfect for LHCb acceptance (400 mrad)
- About 1 strange hadron per collision (compared to  $\sim 10^{-3}$   $B_s^0$  mesons)
- Reconstruction and trigger however bring this number down
- LHCb fully instrumented in this region

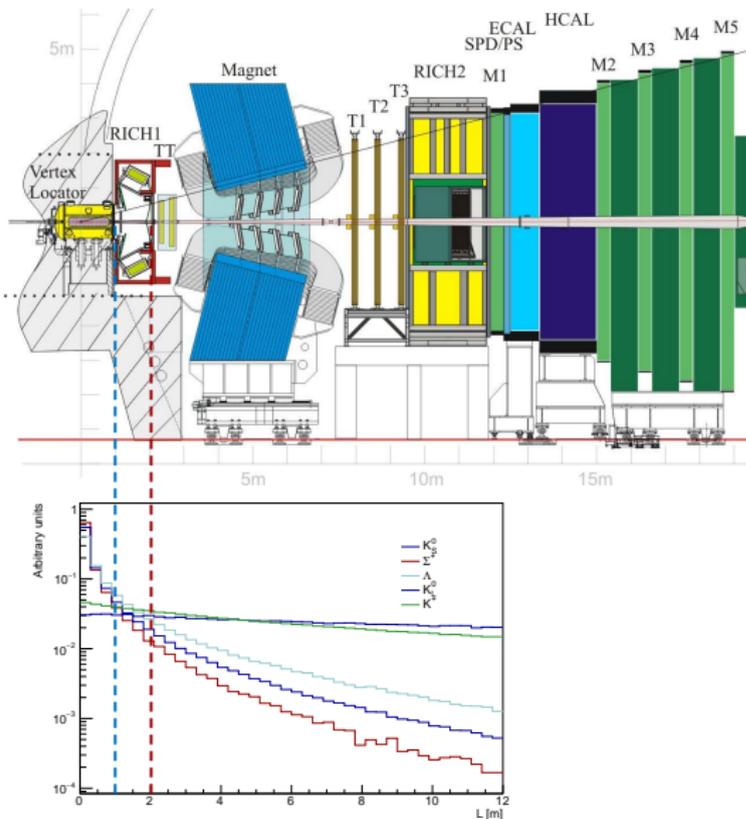


Average particles in LHCb acceptance  
per minimum bias event  
at  $\sqrt{s} = 13$  TeV



# Setting the (long) stage

## Reconstruction and trigger of strange hadrons in LHCb Run 1-2



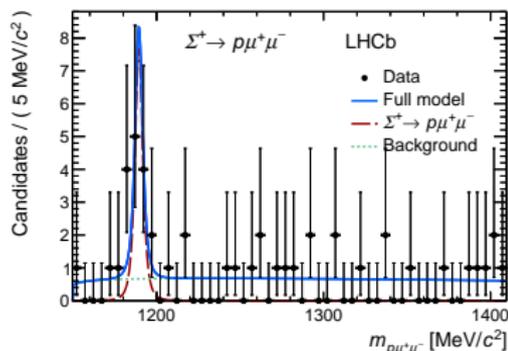
- About 50% lifetime acceptance for  $K_S$  and hyperons
- Different reconstruction methods for the daughter tracks
- Efficiency limited by hardware trigger
  - ★ LHCb trigger designed for heavy flavours
  - ★ Muon (hadron) L0 trigger require  $p_T > [1 - 5] \text{ GeV}$
  - ★ **Too hard for primary strange hadrons**
- Software trigger highly customisable:  
dedicated lines already in 2012
- Since 2016 dedicate software reconstruction for soft muons



# Strange physics at LHCb with Run 1 (2011-2012) and 2 (2015-2018)

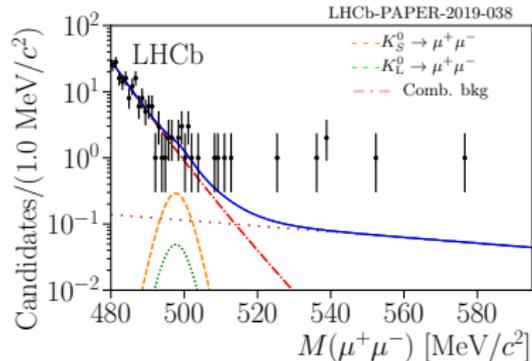
## $\Sigma^+ \rightarrow p\mu^+\mu^-$ - PRL 120, 221803

- Search performed with  $3\text{fb}^{-1}$  revealed  $4.1\sigma$  evidence for the  $\Sigma^+ \rightarrow p\mu^+\mu^-$  decay
- Branching fraction  $(2.2^{+1.8}_{-1.3}) \times 10^{-8}$
- No sign of structure in dimuon mass, excluding HyperCP anomaly central value



## $K_S^0 \rightarrow \mu^+\mu^-$ - EPJ.C, 77 10(2017)678 - LHCb-PAPER-2019-020 - Accepted by PRL

- Search with full dataset (About  $8\text{fb}^{-1}$ )
- Dedicated muon identification developed
- Dedicated software trigger since 2012
- World best limit on  $K_S^0 \rightarrow \mu^+\mu^-$ :  
 $\mathcal{B}(K_S^0 \rightarrow \mu^+\mu^-) < 2.1 \times 10^{-10}$
- Three orders of magnitude improvement w.r.t previous experiments



# LHCb Upgrade data-taking

## LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate  
(full rate event building)

### Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

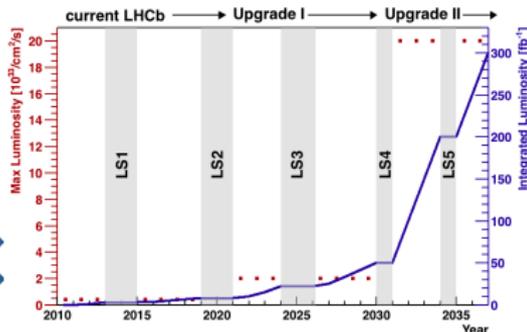
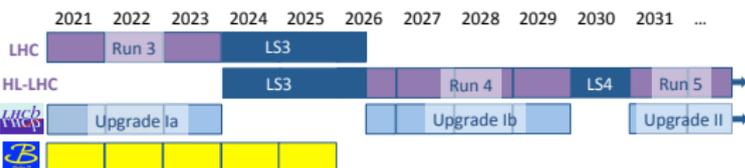
Add offline precision particle identification and track quality information to selections  
Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage

- Upgraded detector for 40 MHz full readout
- $\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \Rightarrow$  about  $5 \text{ fb}^{-1}$  per year
- L0 hardware trigger is removed in Run 3 (2021)
- HLT run directly on collision data
- Efficiencies one to two orders of magnitude larger than Run 1-2
- Future upgrades at LHC HL can give  $50 \text{ fb}^{-1}/\text{y}$

[LHCb-PUB-2018-009]

Fundamental step forward for *strange* physics!

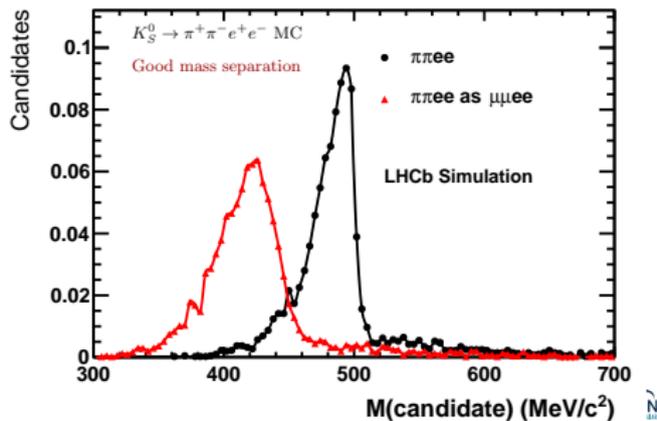
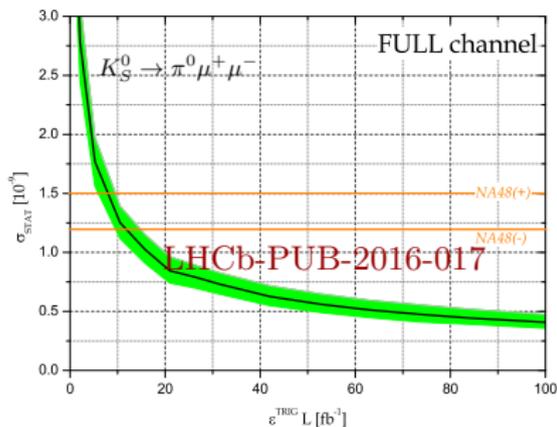


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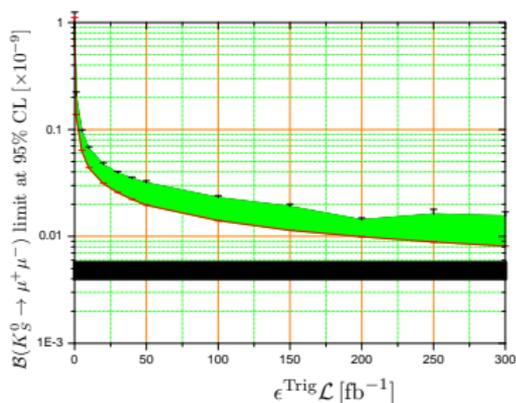
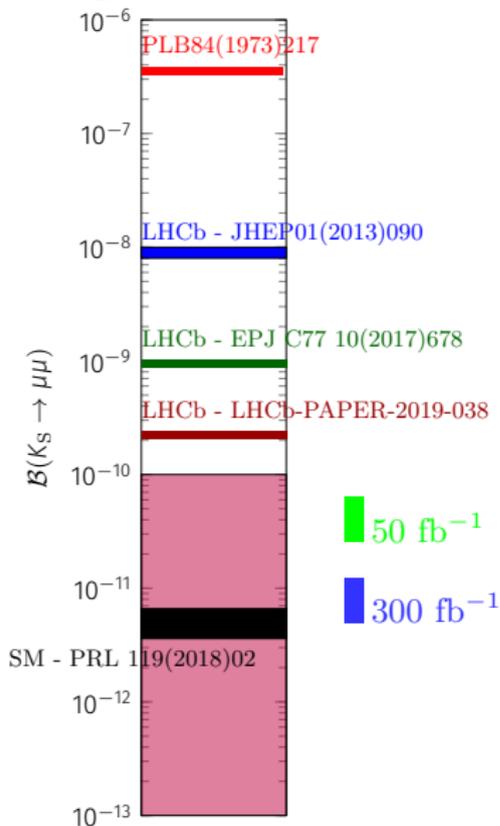


# Sensitivity to $K_S^0$ decays

- Several different sensitivity studies (See Bibliography at the end)
- Simulation and data driven projections
- High yield proxies readily available
- Some uncertainty on real trigger efficiency: results as a function of  $\epsilon\mathcal{L}$
- Electron channels also possible: in the future less penalised
- Neutrals more difficult, but partial reconstruction is an option



# $K_S^0 \rightarrow \mu^+ \mu^-$ prospects



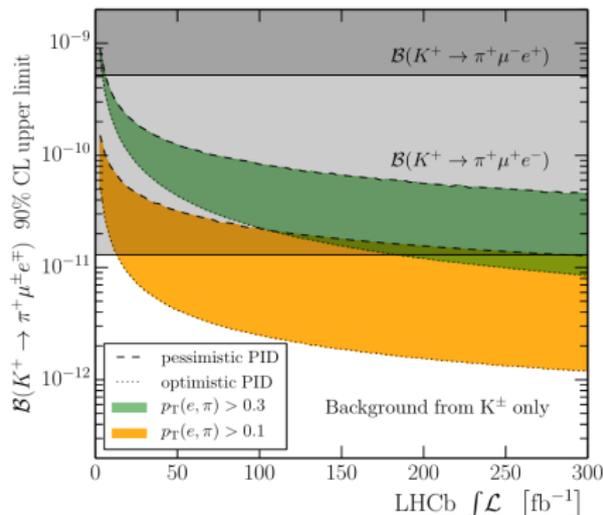
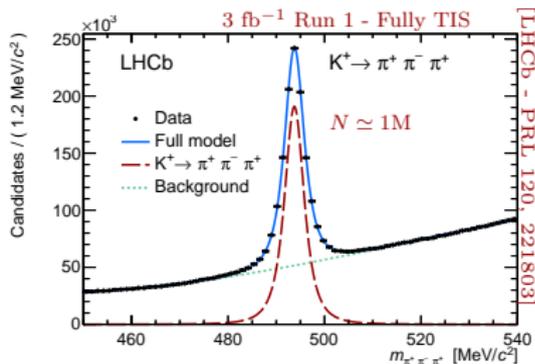
## Future sensitivity to $K_S^0 \rightarrow \mu^+ \mu^-$

- Depends on real trigger efficiencies
- Approach interesting region in Run 2 and Upgrade
- Probe SM in Upgrade II



# Prospects for charged kaons

- Enormous  $K^+$  production but small acceptance
- Measurement of the charged kaon mass is under way to solve long standing disagreement
- With full software trigger  $O(10^{-10})$  single event sensitivity per  $\text{fb}^{-1}$  obtainable
- $K^+ \rightarrow \pi^+ \mu^- \mu^+$  and  $K^+ \rightarrow \pi^+ e^- e^+$  become accessible
- Preliminary estimates of prospects [Borsato et al. PRD 99, 055017 (2019)] [Alves et al. JHEP05(2019)048]
- LHCb could improve limits and maybe touch the  $10^{-13}$  region with full Upgrade (2030s)
- Detailed full simulation studies are however not there yet



## A quick word on hyperons

LHCb can probe different hyperons and decays

- $\Sigma^+$ : Besides the  $\Sigma^+ \rightarrow p\mu^+\mu^-$ , LHCb could improve the  $\Sigma^+ \rightarrow p\gamma$  and try to access the  $\Sigma^+ \rightarrow pe^+e^-$  decay
- $\Lambda$  hyperons
  - \* LHCb could improve the  $\Lambda \rightarrow p\pi\gamma$  branching fraction and try to access  $\Lambda \rightarrow p\pi e^+e^-$
  - \* Large number of BNV / LFV decays constrained by the CLAS collaboration [CLAS PRD.92.072002] could be also tested and improved
- For higher S number baryons LHCb could test  $\Delta S = 2$  processes, such as  $\Xi^0 \rightarrow p\pi$  and  $\Omega \rightarrow \Lambda\pi$  improving limits by orders of magnitude



# A glimpse into LHCb possibilities

- Dedicated paper to explore future possibilities
- Approximate simulations (validated on published ones) to get sensitivities
- Countless channels to be probed

Channel	$\mathcal{R}$	$\epsilon_L$	$\epsilon_D$	$\sigma_L(\text{MeV}/c^2)$	$\sigma_D(\text{MeV}/c^2)$	$\mathcal{R}$ = ratio of production $\epsilon$ = ratio of efficiencies
$K_S^0 \rightarrow \mu^+ \mu^-$	1	1.0 (1.0)	1.8 (1.8)	$\sim 3.0$	$\sim 8.0$	
$K_S^0 \rightarrow \pi^+ \pi^-$	1	1.1 (0.30)	1.9 (0.91)	$\sim 2.5$	$\sim 7.0$	
$K_S^0 \rightarrow \pi^0 \mu^+ \mu^-$	1	0.93 (0.93)	1.5 (1.5)	$\sim 35$	$\sim 45$	
$K_S^0 \rightarrow \gamma \mu^+ \mu^-$	1	0.85 (0.85)	1.4 (1.4)	$\sim 60$	$\sim 60$	
$K_S^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$	1	0.37 (0.37)	1.1 (1.1)	$\sim 1.0$	$\sim 6.0$	
$K_L^0 \rightarrow \mu^+ \mu^-$	$\sim 1$	$2.7 (2.7) \times 10^{-3}$	0.014 (0.014)	$\sim 3.0$	$\sim 7.0$	
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	$\sim 2$	$9.0 (0.75) \times 10^{-3}$	$41 (8.6) \times 10^{-3}$	$\sim 1.0$	$\sim 4.0$	
$K^+ \rightarrow \pi^+ \mu^+ \mu^-$	$\sim 2$	$6.3 (2.3) \times 10^{-3}$	0.030 (0.014)	$\sim 1.5$	$\sim 4.5$	
$\Sigma^+ \rightarrow p \mu^+ \mu^-$	$\sim 0.13$	0.28 (0.28)	0.64 (0.64)	$\sim 1.0$	$\sim 3.0$	
$\Lambda \rightarrow p \pi^-$	$\sim 0.45$	0.41 (0.075)	1.3 (0.39)	$\sim 1.5$	$\sim 5.0$	
$\Lambda \rightarrow p \mu^- \bar{\nu}_\mu$	$\sim 0.45$	0.32 (0.31)	0.88 (0.86)	—	—	
$\Xi^- \rightarrow \Lambda \mu^- \bar{\nu}_\mu$	$\sim 0.04$	$39 (5.7) \times 10^{-3}$	0.27 (0.09)	—	—	
$\Xi^- \rightarrow \Sigma^0 \mu^- \bar{\nu}_\mu$	$\sim 0.03$	$24 (4.9) \times 10^{-3}$	0.21 (0.068)	—	—	
$\Xi^0 \rightarrow p \pi^- \pi^-$	$\sim 0.03$	0.41 (0.05)	0.94 (0.20)	$\sim 3.0$	$\sim 9.0$	
$\Xi^0 \rightarrow p \pi^-$	$\sim 0.03$	1.0 (0.48)	2.0 (1.3)	$\sim 5.0$	$\sim 10$	
$\Omega^- \rightarrow \Lambda \pi^-$	$\sim 0.001$	$95 (6.7) \times 10^{-3}$	0.32 (0.10)	$\sim 7.0$	$\sim 20$	
Channel	$\mathcal{R}$	$\epsilon_L$	$\epsilon_D$	$\sigma_L(\text{MeV}/c^2)$	$\sigma_D(\text{MeV}/c^2)$	
$K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$	1	1.0 (0.18)	2.83 (1.1)	$\sim 2.0$	$\sim 10$	
$K_S^0 \rightarrow \mu^+ \mu^- e^+ e^-$	1	1.18 (0.48)	2.93 (1.4)	$\sim 2.0$	$\sim 11$	
$K^+ \rightarrow \pi^+ e^- e^+$	$\sim 2$	0.04 (0.01)	0.17 (0.06)	$\sim 3.0$	$\sim 13$	
$\Sigma^+ \rightarrow p e^+ e^-$	$\sim 0.13$	1.76 (0.56)	3.2 (1.3)	$\sim 3.5$	$\sim 11$	
$\Lambda \rightarrow p \pi^- e^+ e^-$	$\sim 0.45$	$< 2.2 \times 10^{-4}$	$\sim 17 (< 2.2) \times 10^{-4}$	—	—	
Channel	$\mathcal{R}$	$\epsilon_L$	$\epsilon_D$	$\sigma_L(\text{MeV}/c^2)$	$\sigma_D(\text{MeV}/c^2)$	
$K_S^0 \rightarrow \mu^+ e^-$	1	1.0 (0.84)	1.5 (1.3)	$\sim 3.0$	$\sim 8.0$	
$K_L^0 \rightarrow \mu^+ e^-$	1	3.1 (2.6) $\times 10^{-3}$	13 (11) $\times 10^{-3}$	$\sim 3.0$	$\sim 7.0$	
$K^+ \rightarrow \pi^+ \mu^+ e^-$	$\sim 2$	3.1 (1.1) $\times 10^{-3}$	16 (8.5) $\times 10^{-3}$	$\sim 2.0$	$\sim 8.0$	



## Summary and conclusions

- *LHCb expanding its physics reach towards strange physics complementary to the core program*
- Encouraging Run 1-2 results on  $K_S^0 \rightarrow \mu^+ \mu^-$  and  $\Sigma^+ \rightarrow p \mu^+ \mu^-$
- Large samples available already on tape fully exploiting existing data
- Run 2 giving new results with improved trigger
- Upgrade trigger will allow unprecedented sensitivities on many channels
- Complementary to  $K_L^0$  and  $K^+$  dedicated experiments
- **LHCb major player for  $K_S^0$  and hyperons rare decays**



# Bibliography

## LHCb Collaboration

### Papers

- Evidence for the rare decay  $\Sigma^+ \rightarrow p\mu^+\mu^-$  [Phys. Rev. Lett. 120, 221803 (2018)] [LHCb-PAPER-2017-049] [hep-ex/1712.08606]
- Improved limit on the branching fraction of the rare decay  $K_S^0 \rightarrow \mu^+\mu^-$  [LHCb-PAPER-2017-009] [hep-ex/1706.00758] [Eur. Phys. J. C, 77 10 (2017) 678]
- Search for the CP-violating strong decays  $\eta \rightarrow \pi^+\pi^-$  and  $\eta' \rightarrow \pi^+\pi^-$  [LHCb-PAPER-2016-046] [hep-ex/1610.03666] [Physics Letters B 764 (2017) 233-240]
- Search for the rare decay  $K_S^0 \rightarrow \mu^+\mu^-$  [LHCb-PAPER-2012-023] [hep-ex/1209.4029] [JHEP 01 (2013) 090]

### Public notes

- Physics case for an LHCb Upgrade II [LHCb-PUB-2018-009][arXiv/1808.08865]
- Low  $pr$  dimuon triggers at LHCb in Run 2 [LHCb-PUB-2017-023]
- Sensitivity of LHCb and its upgrade in the measurement of  $\mathcal{B}(K_S^0 \rightarrow \pi^0\mu^+\mu^-)$  [LHCb-PUB-2016-017]
- Feasibility study of  $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$  at LHCb [LHCb-PUB-2016-016]
- Reconstruction of charged kaons LHCb-PUB-2014-032

### Others

- Alves A. A. et al. “Prospects for Measurements with Strange Hadrons at LHCb” [JHEP05(2019)048]
- Borsato et al. “The strange side of LHCb” [Phys. Rev. D 99, 055017 (2019)]

